Renewable and Sustainable Energy Reviews 14 (2010) 2819–2829

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Review on free cooling of buildings using phase change materials

V. Antony Aroul Raj [a,1], R. Velraj [b,*]

[a] Department of Mechanical Engineering, Easwari Engineering College, Bharathi Salai, Ramapuram, Chennai, 600089, India
[b] Department of Mechanical Engineering, Anna University Chennai, Chennai, India

ARTICLE INFO

Article history:
Received 14 May 2010
Accepted 7 July 2010

Keywords:
Free cooling
Green building
PCM
LHTES
Natural ventilation

ABSTRACT

The concept of Green building is gaining importance in the present energy scenario and related environmental issues. Free cooling or ventilation cooling is truly a green concept since even 1 g of carbon is not burnt for the purpose of cooling. Also it ensures that a good indoor air quality is maintained in the building. In this paper a detailed review of work carried out by various researchers on free cooling or ventilation cooling is presented. In addition the major challenges and facts posed in the use of phase change material for free cooling system design such as thermal resistance of air and phase change materials, geometry of encapsulation are discussed in detail. Also the method of energy efficient charging and discharging, effect of phase change temperature, insulation and geographical location are also discussed in this paper. This paper also provides lists the PCM candidates used for free cooling.

Contents

1. Introduction

A comfortable home with minimum energy consumption is the dream of the common man, governments and researchers. In the present energy and environmental scenario there is no need to justify the need to minimize the energy consumed by building space cooling systems. Earlier the researchers were interested in reducing the cost of energy and conserve the depletion of fossil

* Corresponding author at: AU FRG Institute for CAD/CAM, Anna University Chennai, Sardar Patel Road, Chennai, 600004, India. Tel.: +91 44 2235 8051; fax: +91 44 2235 1991.
E-mail addresses: antonyaroulraj@rediffmail.com (V.A.A. Raj), velrajr@annauniv.edu, velrajr@gmail.com (R. Velraj).
[1] Tel.: +91 9841143112.

1364-0321/$ – see front matter
doi:10.1016/j.rser.2010.07.004

fuels. But now the motivation has changed from these goals towards minimizing the carbon dioxide production from the environmental perspective [1]. Energy consumption for space cooling in a building can be reduced by various methods. Passive cooling technique is one such method by which the green house gas emissions can be reduced. Passive cooling techniques utilize principles involving design of micro climate, shading and thermal capacitance to reduce the cooling load. Natural heat sinks are required to dissipate the excess heat of a building by convective, evaporative, radiative principle and by ground cooling [2]. Building cooling can be achieved by two methods

1. Envelope design to reduce the heat entry into the building.
2. Passive and hybrid cooling techniques.

1.1. Envelope design

The indoor temperature of a building is dependent on climatic condition of a place (outdoor temperature, wind velocity, solar radiation), etc., building structure and building thermo physical properties of building materials (wall thickness, area ratio of window to wall, thermal conductivity and specific heat of wall material), etc., indoor heat source and air change rate [3]. Insulation acts as a barrier to heat flow and is essential to keep a building warm in winter and cool in summer. A well insulated and well designed home will provide year-round comfort, reducing cooling and heating energy cost. This, in turn, will reduce greenhouse emissions. Building thermal mass acts like a thermal battery. In cold regions, during daytime it absorbs heat from the sun, keeping the building comfortable and at night the same thermal mass can release the heat. Correct use of thermal mass can delay heat flow through the building envelope by as much as 10–12 h producing a warmer house at night in winter and a cooler house during the day in summer.

Present researches on reflective material for outdoor wall painting have led to the development of suitable materials for solar cooling load reduction. Reflective material when compared to the conventionally used coating material of same color results in a reduction in the surface temperature of about 15 °C. Solar control of transparent components comes from the switchable glazing technology. Technology on electro chromic glazing has been improved and it is currently used for load reduction. Combination of the cool material with green space and heat sinks can reduce the inside building temperature [4].

1.2. Passive cooling techniques

The types of passive cooling techniques are:

(a) Earth to air heat exchangers (buried pipes).
(b) Evaporative cooling system.
(c) Ventilation techniques.

1.2.1. Earth to air heat exchangers

Air is drawn from the environment using an electric fan and cooled by circulating air through the underground duct. The coldness of earth is transferred to air and it is flown into the building. It was verified experimentally that 2–5 °C reduction of peak indoor temperature can be obtained as the depth of earth to air heat exchanger ranges between 1.5 and 6.5 m, respectively. Many building have been designed and monitored and the performance of this concept is proven [4].

1.2.2. Evaporative cooling

Direct evaporating cooling device uses evaporative principle to cool the air entering the building. Droplets of water when evaporated absorb the heat of evaporation from the air and in the process the air gets cooled.

1.2.3. Ventilation techniques

Outdoor air is pumped into the building when the ambient temperature is less for cooling purpose and also to meet the fresh air requirement based on the occupancy. Ventilation techniques contribute to a more comfortable and healthy indoor environment. The types of Ventilation techniques for a low energy building are:

1.2.3.1. Natural ventilation. There will be natural air flow around these buildings. Here the ventilation is controlled by the occupants by opening the windows.

1.2.3.2. Advanced natural ventilation. Here the flow and the direction of the ventilating air are controlled by natural force other than windows such as thermal chimneys and wind towers. Solar thermal chimneys are the natural draft components using the solar energy to build up stack pressure and thus a driving air flow through the chimney. In a wind tower, air enters the towers of the wind ward facade and leaves at the lower part to the inside of the building. Air may be cooled by convective or evaporative principle through the tower.

1.2.3.3. Mechanical ventilation. These buildings usually have a central fan or local fans that provide ventilation air. The fan provides the cooling and ventilation air requirement of the building.

1.2.3.4. Night ventilation. Night ventilation is a method by which the structural components is cooled down using cold night air, thus providing reduced temperature of indoor air conditions for the following day. In places where the daily diurnal range of the ambient temperature are high and the low night temperatures are suitable for night cooling, night ventilation can be used. This ventilation system uses a fan to enable accelerated night cooling using ambient air for ensuring sufficient night cooling. However, in the urban location due to increase in air temperature and decrease in wind velocity the efficiency of the night ventilation is decreased [5].

1.3. Free cooling

The cooling potential of a mechanical ventilation system can be improved by the integration of short term latent heat thermal energy storage systems (LHTES). The LHTES stores the coldness of the ambient air during the night and supplies during the daytime. This process is called free cooling. In short, free-cooling is the method of storing outdoors coolness during the night, and supply to indoor air during the day. The main advantages of free cooling are cooling with reduction of green house gases and excellent indoor air quality maintenance inside the building. Since the temperature difference between day indoors and night outdoors is small, phase change material is the best storage option. Free cooling systems perform better in the place where the diurnal temperature range is greater than 15 °C. If the melting temperature of the phase change materials is at the middle of the diurnal extreme temperatures, then equal temperature difference is available for charging and discharging.

2. Experiments on free cooling

From the literature, the first experiment on free cooling/ventilation cooling was reported by Turnpenny et al. [6]. In this work, the coldness of the night air is stored in the PCM and discharged during the daytime. Heat pipes are embedded in PCM to enhance the heat transfer between air and PCM as shown in Fig. 1. Theoretical modeling of the proposed system is also done in this

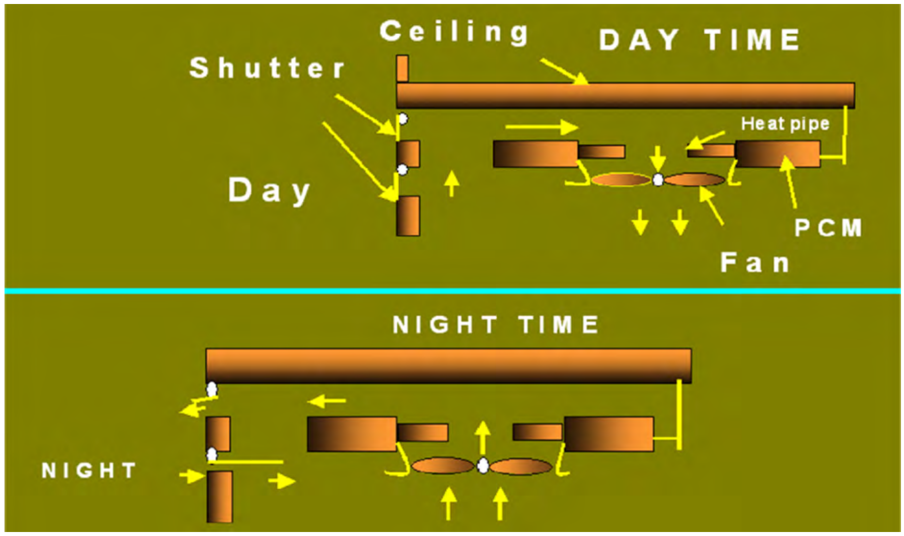

Fig. 1. System proposed by Turpenny et al.

work. The heat transfer rate was approximately 40 W over a melting period of 19 h for a temperature difference between air and PCM of 5 °C. An improvement in the design of the same system was reported by Turpenny et al. [7]. A ceiling fan model with three blades with a sweep diameter of 1200 mm and air movement of 3 m^3/s is used. At night the cool outside air is drawn in and passed over the heat pipe using the ceiling fan blowing downwards. The warm air is let out through the exit vent. During the daytime vents are closed and ceiling fan blow air downward to cool the room. Heat transfer rate was measured and found to be 200 W which was sufficient to take care of the summer load.

Next comprehensive work on free cooling was done by Yanbing et al. [8]. In this work at night, the outdoor cool air is blown through the phase change material package bed system to charge coldness of air to PCM as shown in Fig. 2. During daytime, heat is transferred to LHTES system, and the coldness stored by PCM at night is discharged to the room. The air flow rate was controlled to meet different cooling load demand at daytime. The room air temperature is reduced in Night Ventilation system because of free cooling. First feasibility study of a free cooling system was done by Zalba et al. [9,10]. In this work, an experimental installation flat plate PCM encapsulate as shown in Fig. 3. was used, for PCMs with a melting temperature around 20–25 °C. The major advantages of flat plate encapsulate are (i) the melting and freezing process of a PCM on a plate surface is symmetric, (ii) heat transfer in the PCM can be controlled with the selected thickness of the encapsulation and (iii) high area to volume ratio of storage is obtained. The system parameters analyzed are energy to volume ratio charging and discharging rate. The temperatures of the air during melting (discharging) of the PCM studied were 28 and 30 °C. The temperatures of the air selected during freezing (charging) of the PCM were 16 and 18 °C. In order to achieve maximum heat transfer, air flow rate was selected to get a Biot number of near one.

The solidification process was faster (i) when the thickness of the encapsulates was lower (ii) the temperature difference between air and melting temperature of the PCM was higher and (iii) the air flow rate was higher. Solidification time is lesser and melting time is more because of free convection in the liquid phase.

Marin et al. [11] made improvement to the experiment by Belen Zalba by including graphite compounded material with the

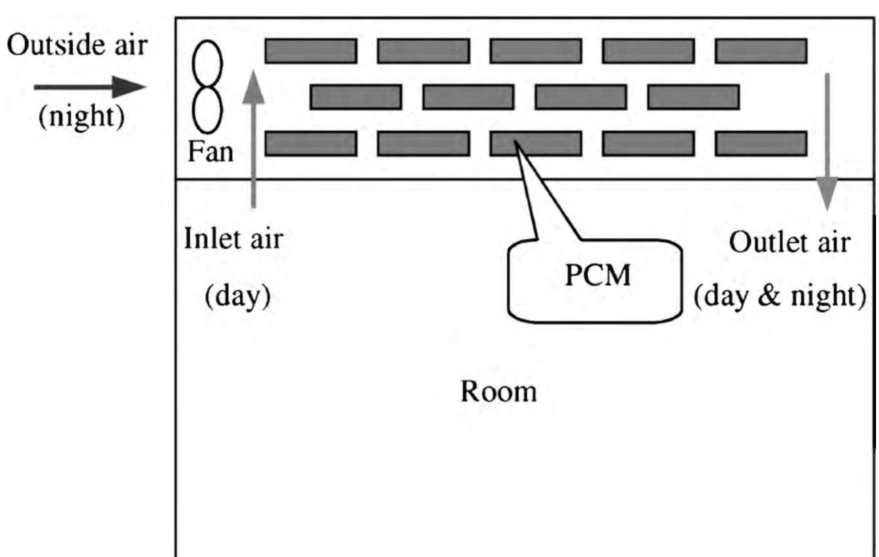

Fig. 2. System proposed by Yanbing et al.

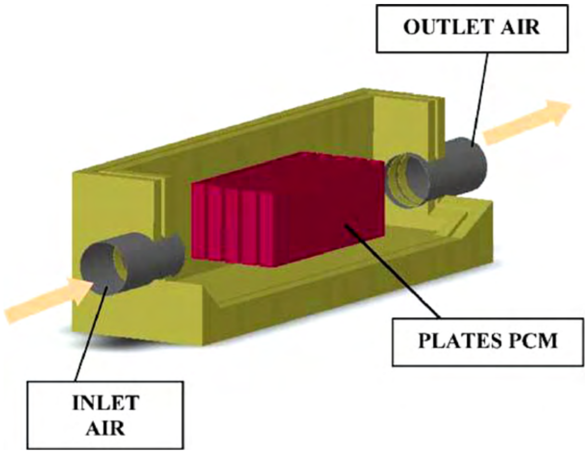

Fig. 3. Heat exchanger set up of Belen Zalba et al.

paraffin PCM for heat transfer enhancement in PCM. Due to graphite addition thermal conductivity is increased in the PCM without much reduction in energy storage. Other advantages of adding graphite are the decrease in sub cooling of salt hydrates and the decrease of volume change in paraffin. These plates contain alternatively the PCM and the composite with the PCM embedded in a graphite matrix shown in Fig. 4. It was found that the great reduction of time, about one half in the case of using the graphite matrix as compared with the PCM only. But the reduction of the energy stored between 12% and 20%, based on the storage volume occupied by the graphite.

Nagano et al. [12] studied the potential for manganese nitrate hexa-hydrate mixture an inorganic PCM as candidate for cooling to store the cold suitable for free cooing temperature range. Thermal response, mass required, toxicity and corrosion properties of this material are studied in detail. It was found that the thermal properties of manganese nitrate hexa-hydrate gave a high potential as PCM for TES in cooling systems. Almost all the chlorides are effective in modulating the melting point of manganese nitrate hexa-hydrate. $MnCl_2{\cdot}4H_2O$ is used as an effective additive for the modulation of the melting point, reduction of super cooling and heat of fusion.

Takeda et al. [13,14] developed a ventilation system utilizing thermal energy storage using phase change material granules. In this work an experimental ventilation system shown in Fig. 5 that ensures direct heat exchange between ventilation air and granules containing phase change material (PCM) was fabricated and tested. Outlet temperature of air is measured when the inlet air temperature was varied periodically to simulate changes of outdoor ambient air temperature. The results showed that the outlet air temperature was stabilized and remained within the phase change temperature range. Packed PCM granules are kept in a rectangular parallel-piped duct made of 100 mm thick thermal insulation boards as shown in Fig. 5. The duct is installed vertically and PCM granules are packed in the center of the duct. Granules made by RUBITHERM GmbH were used as PCM granules in the experiment. The granules have a particle diameter of 1–3 mm and consist of 65% ceramic materials and 35% paraffin hydrocarbon by weight. The packed bed has high capacity to stabilize diurnal fluctuations of outdoor air temperature. A ventilation system for reducing ventilation load was examined through computer simulation for eight representative cities of Japan. This revealed how different climatic temperature conditions would affect required heat storage capacity.

Nagano et al. [15] embedded PCM directly on floor boards in the form of granules of several millimeters in diameter. This PCM packed bed is permeable to air and so it is suitable for use in floor supply air conditioning systems. During night, circulation of cool air through the under floor space allows cool energy to be charged to the concrete slab, floor board and PCM packed bed. During the daytime cool energy can be used to remove the cooling load in the room. This method shown in Fig. 6 is superior compared to a sensible storage system because building mass thermal storage capacity is limited.

Arkar and Medved [16,17] studied the influence of thermal property data of phase change material on the result of numerical model developed for a packed bed storage system used for free cooling. A packed bed numerical model was modified to take into account the non-uniformity of the PCM's porosity and the fluid's velocity which is due to small tube-to-sphere diameter ratio. Based on the parametric analysis a free cooling system was suggested by the same authors [18], that comprises of a single cylindrical LHTES containing an optimized diameter of spheres with an encapsulated PCM, with a small pressure drop. In this study as shown in Fig. 7, the LHTES is filled with spheres with encapsulated PCM. The storage aspect ratio, L/D, is 1.5 with a small pressure drop and thus a low electrical power of the fans. Two LHTESs were used in this system, one operating with ambient air and the other with recirculated air. Thus the overall cooling efficiency of free cooling using latent heat storage integrated system of a low energy building is increased [19].

Medved and Arkar [20] studied the free-cooling potential for different climatic locations in Europe. The size of the LHTES was optimized on the basis of the calculated cooling degree-hours (CDH). Six representative cities were selected in Europe that covers a wide range of different climatic conditions. Numerical investigations of the free-cooling potential were made for a time period of 3

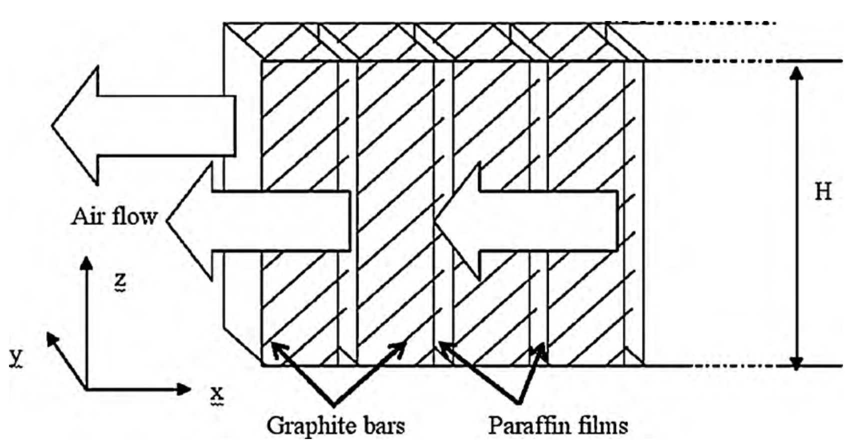

Fig. 4. PCM-graphite arrangement of Marin et al.

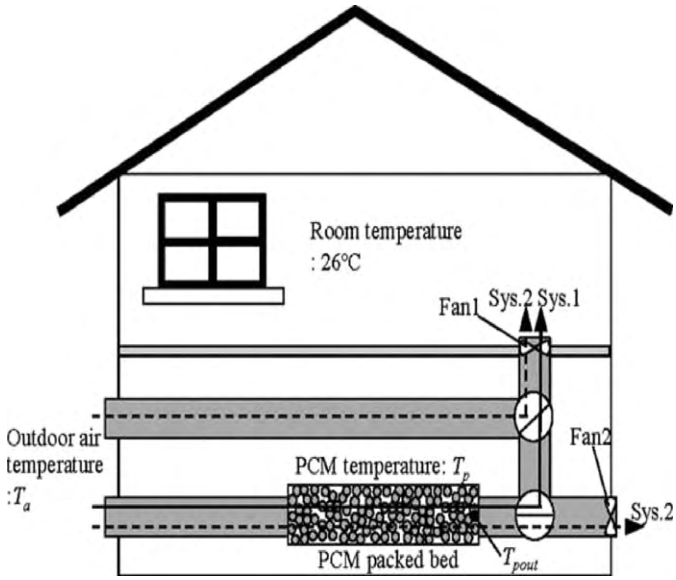

Fig. 5. Conceptual system proposed by Takeda et al.

summer months and optimal mass was finalized for the studied system. For a comparison of the free-cooling efficiency the CDH were determined for the same time period. LHTES optimization was made for selected parameters, such as the PCM's phase change temperature range, the PCM's melting temperature, and the ratio of the PCM's mass to the air volume flow rate.

Based on the outcome of the experiments of Zalba et al. two different real-scale prototypes of air to PCM heat exchangers were designed and tested by Lazaro et al. [21] following the standards ANSI/ASHRAE standard 94.1-2002 (method of testing active latent-heat storage devices based on thermal performance). In this method, in order to obtain accuracy in the measurement of air flow and the temperature difference between the inlet and the outlet, precision thermopiles were used in the measurement of inlet and outlet temperatures. Two prototypes used in Fig. 8 were tested for heat transfer between air and PCM. Prototype 1 shown in Fig. 8(a) uses aluminum pouches filled with an inorganic PCM and air is passed over it. Air was made to flow parallel to the pouches from bottom to top. When tested with constant inlet temperature, the results showed that cooling rates were low and the melting time is double the melting design time. The second prototype was designed using aluminum panels filled with organic PCM as shown in Fig. 8(b). The set up was tested with different air flow rates in prototype 2 and it was observed that it has influence on the melting time and cooling power. This indicates that heat transfer by conduction inside the PCM becomes controlling compared to heat convection to air. An empirical model for a real-scale prototype of a PCM-air heat exchanger is discussed by Lazaro et al. [22]. From the experimental results, an empirical model for simulating the thermal behavior in the tested heat exchanger in different cases was prepared for evaluating the technical viability of its application. Since the thermal properties of PCM vary with temperature, a PCM-heat exchanger design must be based on transient analysis. This work shows that PCM selection criteria must include the power demand.

3. Phase change materials used in free cooling

For efficient free cooling it is necessary to select a PCM that is suitable for the climatic conditions and to determine the optimal mass of the PCM for the selected geometry and performance parameters of the LHTES. The desirable properties of PCM materials are high latent heat of fusion, high thermal conductivity, small volume change during phase change, least sub cooling while freezing, should possess chemical stability, non-toxic and cheap. The PCM used for free cooling should have melting temperature ranging from 15 to 30 °C. Detailed discussions about various types of PCM and their properties are given in various reviews [23–26] and [27]. The PCM are classified as organic, inorganic and eutectic

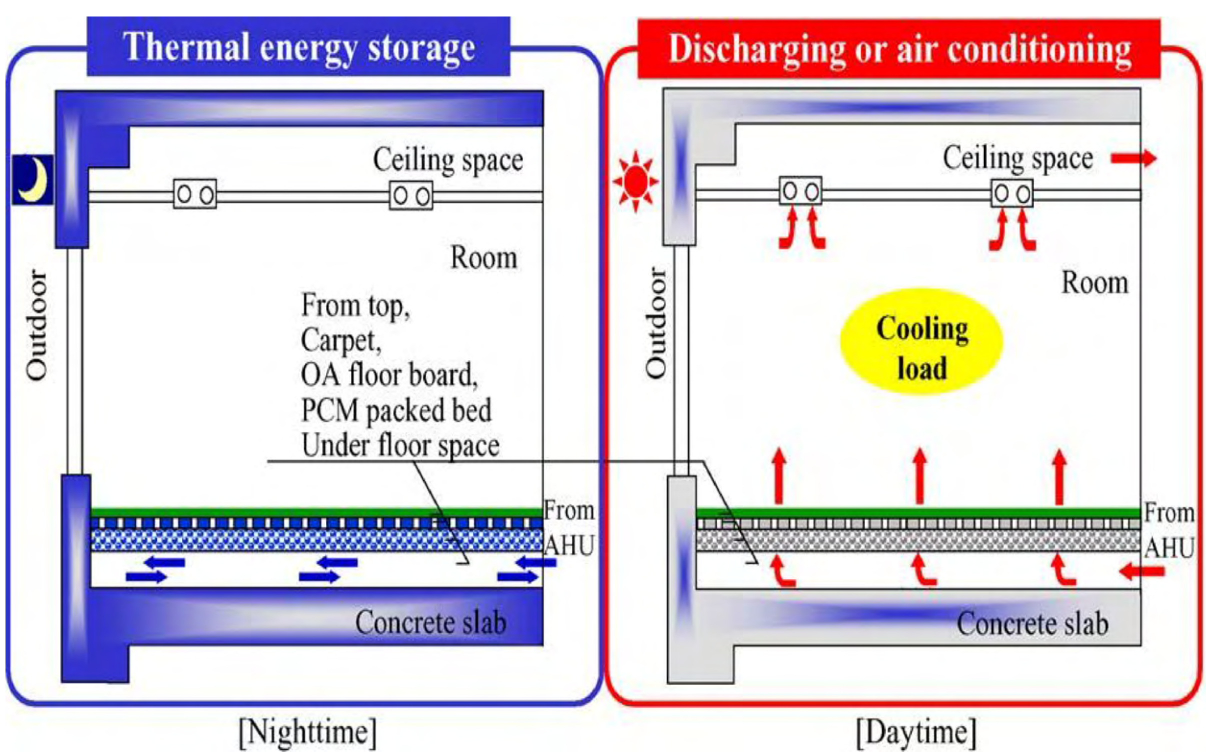

Fig. 6. Conceptual system proposed by Nagano et al.

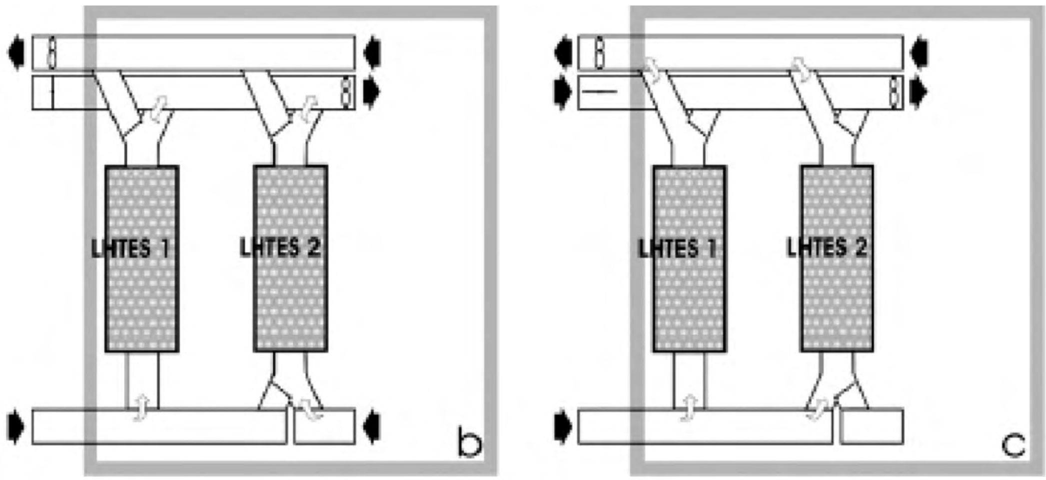

Fig. 7. Daytime and night time free cooling operation mode as proposed by Arkar and Medved.

materials. The inorganic PCMs (Tables 1 and 2) have a higher thermal conductivity and energy storage density [28–37]. Also they are non-inflammable and cheap. But because of their corrosiveness, super cooling and phase segregation during the phase change these materials are not usually used for free cooling. To overcome these problems, normally nucleating and thickening agents are to be added with the inorganic PCMs. Due to the absence of these problems organic PCMs (Table 3) becomes attractive. However flammability, volume change and lower heat conductivity are concerns in recent studies. Organic PCMs [38–43] are classified as paraffin's and non-paraffin. Euctectic or non-euctectic mixtures of organic and inorganic PCMs could be used to get the desired melting point. Most of the experiments conducted so far in free cooling uses commercial grades of PCMs (Table 4) made by the manufacturers for which the properties are available in the websites [44–49].

4. Heat transfer problems and design considerations in free cooling

Free cooling works well in a place where the atmospheric diurnal temperature range is more than 15 °C. This temperature range is achievable in the desert and interior regions. For the place where the diurnal temperature range is less than 15 °C, adopting the free cooling concept requires careful design consideration. Hence the selection of PCM and achieving the required heat transfer for the free cooling requires careful consideration.

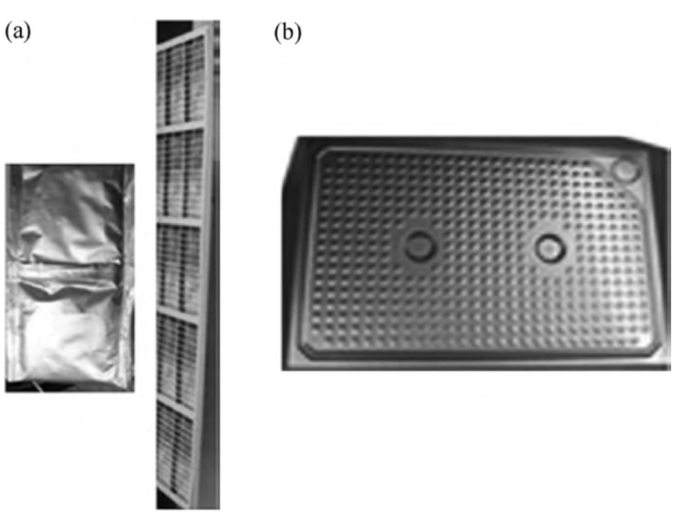

Fig. 8. Encapsulates used by Lazaro et al. (a) pouches (b) flat panels.

4.1. Thermal resistance of air and PCM

In all the free cooling applications air is used as the heat transfer fluid and PCM is used as the storage material. The surface heat transfer coefficient with the air as the working medium is normally a low value. Usually fins are provided on the air side to increase the surface area of heat transfer. During the initial part of the solidification and melting the conduction resistance offered by PCM material will be very low and hence high heat transfer can be achieved by having higher surface heat transfer coefficient (i.e.) by circulating air at higher velocity. But at later stages the variable conduction resistance offered by the PCM is very high, and hence the velocity of air circulation can be reduced to match PCM resistance with air resistance.

Most of the researchers have used paraffin (organic PCM) as the phase change materials which are having a very low thermal conductivity. Though it has no segregation problem in the repeated cycling normally encountered in inorganic salt hydrates, the thermal conductivity is less. In order to compensate the low thermal conductivity heat transfer enhancement techniques like introduction of fins [50,51], inserting the metal matrix in PCM [52], PCM packed with lessing rings [53–55], introduction of graphite in PCM base material in fibrous form [56–58] and shape stabilized form [59], use of heat pipes [6,7] as shown in Fig. 9 are employed.

Table 1
Inorganic PCMs for free cooling.

Compound	Melting point (°C)	Heat of fusion (kJ/kg)	References
$KF{\cdot}4H_2O$	18.5	231	[28,29]
$Mn(No_3)_2{\cdot}6H_2O$	25.8	125.9	[12]
$CaCl_2{\cdot}6H_2O$	29	190.8	[30–33]
$Na_2SO_4{\cdot}10H_2O$	32	251	[28,29]

Table 2
Inorganic eutectics for free cooling.

Compound	Melting point (°C)	Heat of fusion (kJ/kg)	References
48% $CaCl_2$+4.3% NaCl+0.4% KCl+47.3% H_2O	26.8	188	[29]
47% $Ca(NO_3)_2{\cdot}4H_2O$+53% $Mg(NO_3)_2{\cdot}6H_2O$	30	136	[29]
60% $Na(CH_3COO){\cdot}3H_2O$+40% $CO(NH_2)_2$	30	200.5	[35]

Table 3
Organic PCMs for free cooling.

Compound	Melting point (°C)	Heat of fusion (kJ/kg)	References
Capric acid	30.1	158	[30,31]
Capric–lauric acid	18–19	120	[36,38,40]
Capric acid–myristic acid	21.4	152	[36,42]
Capric acid–palmitic acid	22.1	153	[36,37]
Capric acid–stearic acid	26.8	152	[36,42]
Paraffin C_{16}–C_{18}	20–22	152	[10,29,41]
Paraffin C_{13}–C_{24}	22–24	189	[10,29,41]
Dimethyl sabacate	21	120	[43]
Polyglycol E 600	12.5	129.1	[30,31]
1-Dodecanol	26	200	[40]
Vinyl stearate	27–29	122	[43]
Hexadecane	18.1	236	[44]

4.2. Effect of geometry of the encapsulation container

In a free cooling operation charging time available in accelerated mode will be very less (3–4 h when the ambient temperature is low usually in the early morning hours) hence there is a restriction in the solidification time, solidification thickness and heat transfer surface. Several studies have been made in various configurations like flat plate, cylindrical, shell and tube and spherical encapsulation shown in Fig. 10. With flat plates it is possible to achieve more surface area per unit volume of storage material with low PCM thickness for reducing the solidification time. According to Zalba et al. [9,10] the flat plate configuration with the channel width of 15 mm resulted in a charging time of 4 h and the discharging time of 6 h which is reasonably acceptable for the free cooling. Also they have less weight and volume [60,61]. PCM Cylindrical pipes have lesser fabrication difficulty, comparable heat transfer characteristics and have lower heat loss rate [62–64].

In a shell and tube heat exchanger transfer of heat takes place transfer in the axial and radial directions with increased area of convective heat transfer [65,66]. PCM balls have larger surface area per unit volume compared to cylindrical geometry of length equal to diameter. Heat transfer and pressure drop can be controlled by selecting the size of the balls. Arkar et al. [16–20] have used 25 mm ball and Takeda et al. [13–15] used granulated (micro encapsulated) PCM used of 3 mm size. In the later case the charging time is 1.5 h which is well suited for the free cooling application. However this increases the pressure drop and hence the pumping power of the fan used. Optimizing the size of the encapsulates/granules are

Table 4
Commercial PCMs for free cooling.

Name	Type	Melting temperature	Heat of fusion (kJ/kg)	Density	Manufacturing company's name
RT20	Paraffin	20–22	172	0.87 (0.75)	Rubitherm [45]
RT26	Paraffin	24–28	131	0.88 (0.76)	
RT27	Paraffin	26–28	179	0.87 (0.75)	
ClimSel C 23	Salt hydrate	23	148	1.48	Climator AB [46]
ClimSel C 24	Salt hydrate	24	216	1.48	Climator AB [46]
Climsel C 32	Salt hydrate	32	212	–	Climator AB [46]
STL 27	Salt hydrate	27	213	–	Mitsubishi chemical [47]
S27	Salt hydrate	27	207	–	Cristopia [48]
E17	Salt hydrate	17	143	1.49	Environmental Process Limited [49]
E19	Salt hydrate	19	146	1.48	
E21	Salt hydrate	21	150	1.48	
E30	Salt hydrate	30	201	1.3	

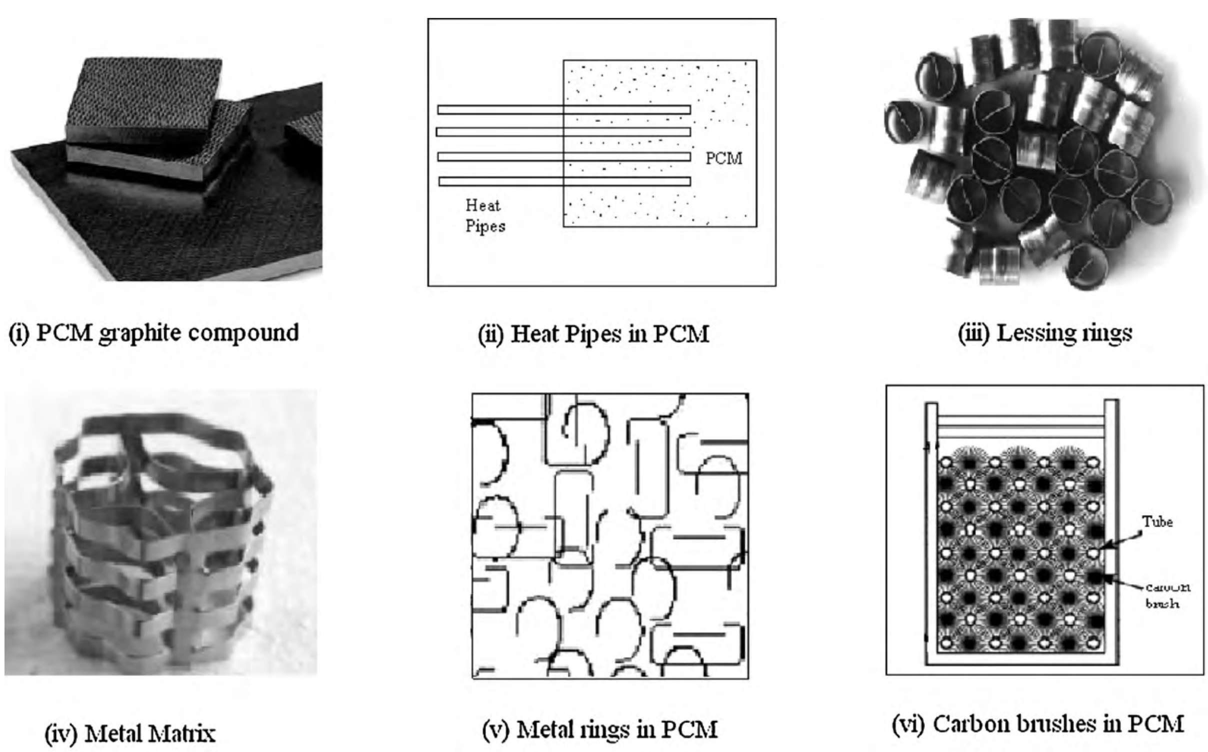

Fig. 9. Heat transfer enhancement techniques in PCM.

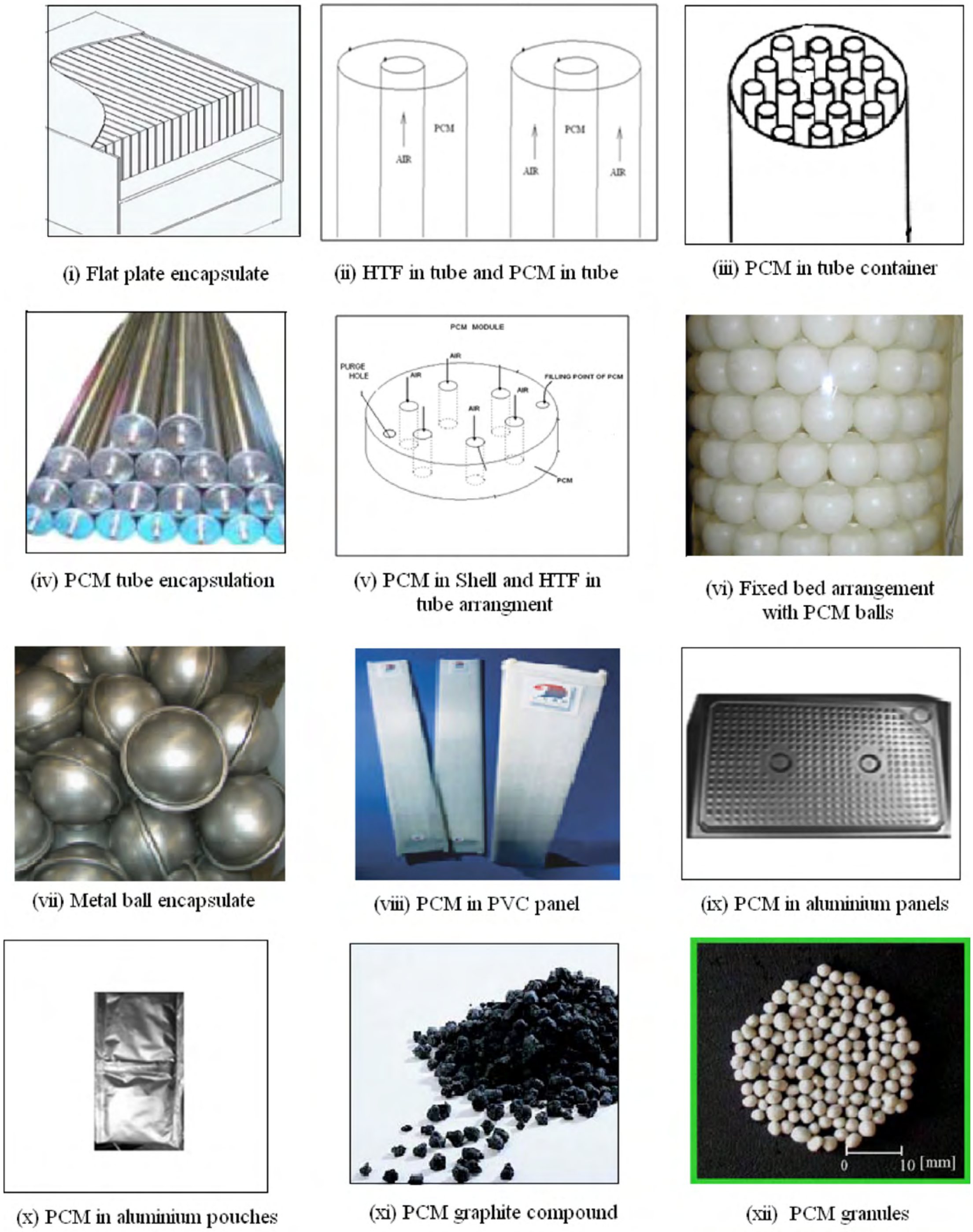

Fig. 10. Various types of PCM encapsulations.

essential for improving energy efficiency. PCM pouches and panels were tested by Lazaro et al. [21,22] and panel was found to be superior to pouches.

4.3. Energy efficient charging and discharging

In the free cooling application the lowest temperature during the day is available for 3–4 h in the early morning. This time period is utilized to charge the cool energy in the PCM. Initial part of charging can be accelerated with higher surface heat transfer coefficient. However during later part of the charging higher heat transfer coefficient may not be useful as the conductive resistance of PCM becomes dominant. Hence fan speed can be reduced during the later part of the charging process so that reduced heat transfer coefficient is in conjunction with inside variable conductive resistance of PCM. Hence while designing free cooling system energy efficient multiple speed fan should be used to achieve the energy efficient charging and discharging.

4.4. Effect of phase change temperature

When the selected PCM has distinct Phase change temperature the PCM cannot accommodate the swing in the ambient air temperature. Hence same PCM cannot be used in all the seasons.

According to Medved and Arkar [20], PCM with a range of phase change temperature is suitable for free cooling as it absorbs heat in varying inlet temperature and accommodates the swing in the ambient air temperature on large number of days. Thus it is construed that the selection of PCM for year-round thermal management is difficult since there is a large swing in the atmospheric temperature in all the seasons. Pasupathy et al. [67,68] suggested two layer of PCM with different melting temperature for year-round thermal management in the roof top of the building. Similar concept of using multiple PCM is also required for free cooling for year-round thermal management.

Most of the PCMs while freezing experience sub cooling. Hence the available temperature potential between the air and the PCM will become very less which reduces the heat transfer rate. Hence the ratio of sensible heat to latent heat stored in the PCM material which is normally defined as the Stefan number should be as low as possible.

4.5. Effect of insulation

Insulation plays an important role in retaining the stored heat in the system, especially when operating with low diurnal temperature difference. If the daytime ambient temperature is high and the system and ducts are not insulated the heat loss to the surrounding will be more through the walls and through the ducts used for conveying cold air to the room. For tropical climates rather than keeping the heat exchanger outside it is better to keep the PCM inside the building using PCM panels and pouches for reducing the heat losses to the ambient.

4.6. Fan energy consumption

The energy required to drive the fan should be as low as possible with maximum heat transfer. For achieving this objective the volume flow rate, pressure drop, and charging time should be reduced in the designed system. Volume flow rate of air is controlled by controlling the velocity of the flow. The velocity of air flow in the heat exchanger considered in the designed system should be less for energy efficient operation. As the solidification progresses, increasing the velocity of the air does not play any role in reducing the solidification time. Also at higher velocities more energy is wasted as turbulent production and dissipation without increasing the heat transfer rate. The pressure drop can be minimized by selecting minimum length of bed in fixed bed system and lesser number of modules in the series arranged modular heat exchanger systems. Modules can be kept in series and parallel combinations. However a parallel combination reduces the pressure drop and increases the rate of heat transfer.

4.7. Effect of geographical location and seasons on free cooling potential

The ambient temperature of place is dependent on the seasonal climate and geographical location. The comfort temperature of the room ranges from 21 to 25 °C. Free cooling concept is site specific and climate dependent. Free cooling is suitable for the interior and desert regions. The benefit is less in the coastal area because temperature moderation is done by sea and land breeze and in places where diurnal temperature variation is less. The effectiveness of the free cooling does not depend on average temperature of a place but it is a strong function of amplitude of the ambient temperature swing [20]. For tropical climates like India the year-round ambient temperature will be above 20 °C. Mechanical cooling will be required during summer. PCM with higher temperature can be used for temperature moderation during summer season for load reduction [67]. Free cooling with low melting temperature PCM can be used during winter. For the places above 20° N latitude, the year-round ambient temperature will not be above 30 °C. Heating will be required during winter. Here free cooling can be effected during summer.

The melting temperature of the PCM should be higher in a warmer climate. The optimum PCM phase change temperature as given by Arkar and co-worker [20] is $T_p = T_a + 2$ K. The variation of the ambient temperature of the air should be on both sides of the melting temperature of the PCM so that atmosphere can act as the heat sink to reject heat during night time. If during summer the ambient temperature of place do not fall below the melting temperature of PCM, it will not be solidified and will not be ready for next day's operation [13].

To estimate the efficiency of a free cooling a concept called as cooling degree hours was introduced by Arkar et al. [19].

$$\mathrm{CDH} = \sum_{i=1}^{n} (T_a - T_o)\delta.$$

n – number of days for which free cooling experiment is conducted.
T_a – ambient temperature.
T_o – outlet temperature of the free cooling system.
δ – 1 h.

If the outlet temperature of the LHTS is reduced, cooling potential by free cooling is increased because of increase in cooling degree hours.

5. Conclusions

In this paper various experimental works carried out by various researchers on free cooling, phase change materials used in free cooling and the heat transfer problems in free cooling are discussed. Free cooling concept is site specific and climate dependent. Free cooling is suitable for the interior and desert regions. The benefit is less in the coastal area because temperature moderation is done by sea and land breeze. Free cooling system requires heat transfer augmentation on air and PCM side. Free cooling requires lesser charging time which can be achieved by larger surface area per storage volume. Discharging can be done as per the load demand requirement. For energy efficient charging velocity of air should be more in the beginning of charging and to be reduced at the later stages. The performance of free cooling system will be good if the Phase change temperature of PCM selected is in the midrange of diurnal temperature variation. The velocity of air flow should be optimized during operation to control the volume flow and pressure drop which decides the capacity of the fan and power consumption.

Acknowledgements

The authors acknowledge TEDA (Tamil Nadu Energy Development Agency) for the financial assistance provided for the research project on Energy efficient buildings. Also the authors acknowledge the contribution of Dr. R.V. Seeniraj, Professor, Department of Mechanical Engineering, Raja Lakshmi Engineering College, Chennai, India for his valuable suggestions and contributions for the improvement of this paper.

References

[1] Holmes MJ, Hacker JN. Climate change, thermal comfort and energy: meeting the design challenges of the 21st century. Energy and Buildings 2007;39:802–14.

[2] Agas G, Matasaggos T, Santamouris M, Argriou A. On the use of atmospheric heat sinks for heat dissipation. Energy and Buildings 1991;179(4): 321–9.
[3] Zhang Y, Zhou G, Lin K, Zhang Q, Di H. Application of latent heat thermal energy storage in buildings: state-of-the-art and outlook. Building and Environment 2007;42:2197–209.
[4] Santamouris M, Pavlo K, Synnefa K, Niachou K, Kolokotsa D. Recent progress on passive cooling techniques, advanced technological developments to improve survivability levels in low income households. Energy and Buildings 2007;39(7):859–66.
[5] Geros V, Santamouris M, Karatasou S, Tsangrassoulis A, Papanikolaou N. On the cooling potential of night ventilation techniques in the urban environment. Energy and Buildings 2005;37:243–57.
[6] Turnpenny JR, Etheridge DW, Ray DA. Novel ventilation cooling system for reducing air conditioning in buildings. Part I: testing and theoretical modeling. Applied Thermal Engineering 2000;20(11):1019–37.
[7] Turnpenny JR, Etheridge DW, Ray DA. Novel ventilation cooling system for reducing air conditioning in buildings. Part II: testing of prototype and theoretical modeling. Applied Thermal Engineering 2000;21(12):1019–37.
[8] Yanbing K, Yi J, Yinping Z. 'Modeling and experimental study on an innovative passive cooling system – NVP system. Energy and Buildings 2003;35:417–25.
[9] Zalba B, Marin JM, Cabeza LF, Mehling H. Free-cooling of buildings with phase change materials. International Journal of Refrigeration 2004;27:839–49.
[10] Zalba B, Marin JM, Sanchez-Valverde B, Cabeza LF. Free cooling; an application of PCMS in TES. In: IEA, ECES IA, annex 17, 3rd workshop; 2002.
[11] Marin JM, Zalba B, Cabeza LF, Mehling H. Improvement of thermal storage using plates with paraffin–graphite composite. International Journal of Heat and Mass transfer 2005;48:2561–70.
[12] Nagano K, Ogawa K, Mochida T, Hayashi K, Ogoshi H. Performance of heat charge/discharge of magnesium nitrate hex hydrate and magnesium chloride hex hydrate mixture to a single vertical tube for a latent heat storage system. Applied Thermal Engineering 2003;23:229–41.
[13] Takeda S, Nagano K, Mochida T, Shimakura K. Development of a ventilation system utilizing thermal energy storage for granules containing phase change material. Solar Energy 2004;77:329–38.
[14] Takeda S, Nagano K, Mochida T, Shimakura K. Thermal characteristics of a direct heat exchange system between granules with phase change material and air. Applied Thermal Engineering 2004;24(14–15):2131–44.
[15] Nagano K, Takeda S, Mochida T. Study of the floor supply air conditioning system using granular phase change material to augment building mass thermal storage-heat response in small scale experiments. Energy and Building 2004;77:329–38.
[16] Arkar C, Medved S. Influence of accuracy of thermal property data of a phase change material on the result of a numerical model of a packed bed latent heat storage with spheres. Thermochimica Acta 2005;438(1–2):192–201.
[17] Arkar C, Vidrih B, Medved S. Numerical modelling of free cooling of low energy building utilizing PCM heat storage integrated into the ventilation system. In: 8th international IEA workshop (annex 17), advanced thermal energy storage trough phase change materials and chemical reactions; 2005.
[18] Arkar C, Medved S. Free cooling of building using PCM heat storage integrated into the ventilation system. Solar Energy 2007;81:1078–87.
[19] Arkar C, Vidrih B, Medved S. Efficiency of free cooling using latent heat storage integrated into the ventilation system of a low energy building. International Journal of Refrigeration 2007;30:134–43.
[20] Medved S, Arkar C. Correlation between the local climate and the free-cooling potential of latent heat storage. Energy and Buildings 2008;40(4):429–37.
[21] Lazaro A, Dolado P, Marin JM, Zalba B. PCM-air heat exchangers for free-cooling applications in buildings: experimental results of two real scale prototypes. Energy Conversion and Management 2009;50:439–43.
[22] Lazaro A, Dolado P, Marin JM, Zalba B. PCM-air heat exchangers for free-cooling applications in buildings: empirical model and application to design. Energy Conversion and Management 2009;50:444–9.
[23] Zalba B, Marin JM, Cabeza LF, Mehling H. Review on thermal energy storage with phase change: materials, heat transfer analysis and applications. Applied Thermal Engineering 2003;23:251–83.
[24] Sharma A, Tyagi VV, Chen CR, Buddhi D. Review on thermal energy storage with phase change materials and applications. Renewable and Sustainable Energy Reviews 2009;13(2):318–45.
[25] Sharma SD, Sagara K. Latent heat storage materials and systems: a review. International Journal of Green Energy 2005;2:1–56.
[26] Tyagi VV, Buddhi D. PCM thermal storage in buildings: a state of art. Renewable and Sustainable Energy Reviews 2007;11(6):1146–66.
[27] Kenisarin M, Mahkamov K. Solar energy storage using phase change materials. Renewable and Sustainable Energy Reviews 2007;11:1913–65.
[28] Naumann R, Emons HH. Results of thermal analysis for investigation of salt hydrates as latent heat-storage materials. Journal of Thermal Analysis 1989;35:1009–31.
[29] Abhat A. Low temperature latent heat thermal energy storage: heat storage materials. Solar Energy Journal 1983;30:313–32.
[30] Dincer I, Rosen MA. Thermal energy storage: systems and applications. John Wiley & Sons Ltd.; 2002.
[31] Lane GA. Low temperature heat storage with phase change materials. International Journal Ambient Energy 1980;1:155–68.
[32] Tyagi VV, Buddhi D. Thermal cycle testing of calcium chloride hexa hydrate as a possible PCM for latent heat storage. Solar Energy Materials and Solar Cells 2008;92(8):891–9.
[33] Kimura H, Kai J. Phase change stability of $CaCl_2{\cdot}6H_2O$. Solar Energy 1984;33(1):49–55.
[34] Zhang Y, Jiang Y, Jiang Y. A simple method, the T-history method, of determining the heat of fusion, specific heat and thermal conductivity of phase-change materials. Measurement Science Technology 1999; 10:201–5.
[35] Li JH, Zhang GE, Wang JY. Investigation of a eutectic mixture of sodium acetate tri hydrate and urea as latent heat storage. Solar Energy 1991;47:443–5.
[36] Kauranen P, Peippo K, Lund PD. An organic PCM storage system with adjustable melting temperature. Solar Energy 1991;46:275–8.
[37] Peippo K, Kauranen P, Lund PD. A multicomponent PCM wall optimized for passive solar heating. Energy & Buildings 1991;17:259–70.
[38] Dimaano MNR, Watanabe T. Performance investigation of the capric and lauric acid mixture as latent heat energy storage for a cooling system. Solar Energy 2002;72:205–15.
[39] Dimaano MNR, Watanabe T. The capric-lauric acid and pentadecane combination as the phase change material for cooling applications. Applied Thermal Engineering 2002;22:365–77.
[40] Hawes DW, Feldman D, Banu D. Latent heat storage in building materials. Energy Building 1993;20:77–86.
[41] Marin JM, Zalba B, Cabeza LF, Mehling H. Determination of enthalpy–temperature curves of phase change materials with the T-history method—improvement to temperature dependent properties. Measurement Science and Technology 2003;14:184–9.
[42] Sarı A. Eutectic mixtures of some fatty acids for low temperature solar heating applications: thermal properties and thermal reliability. Applied Thermal Engineering 2005;25:2100–7.
[43] Feldman D, Shapiro MM, Banu D. Organic phase change materials for thermal energy storage. Solar Energy Materials 1986;13:1–10.
[44] Lazaro A, Gunther A, Mehling H, Hiebler S, Marin JM, Zalba B. Verification a T-history installation to measure enthalpy versus temperature curve of phase change materials. Measurement Science and Technology 2006;17:2168–74.
[45] http://www.rubitherm.com.
[46] http://www.climator.com.
[47] www.mfc.co.jp.
[48] http://www.cristopia.com.
[49] http://www.epsltd.co.uk.
[50] Nagano K. Experiments on fin-effects for increasing heat transfer coefficients during charging heat and heat release between PCMs and thermal medium. In: Paper presented at the IEA annex 17 workshop in Arvika (Sweden) held on 8 June 2004; 2004. Available from http://www.fskab.com.
[51] Agyenim F, Eames P, Smyth M. A comparison of heat transfer enhancement in a medium temperature thermal energy storage heat exchanger using fins. Solar Energy 2009;83:1509–20.
[52] Hafner B, Schwarzer K. Improvement of the heat transfer in a phase-change-material storage. In: Proceedings of the 4th workshop of IEA ECES IA annex 10; 1999.
[53] Velraj R, Seeniraj RV, Hafner B, Faber C, Schwarzer K. Experimental analysis and numerical modelling of inward solidification on a finned vertical tube for a latent heat storage unit. Solar Energy 1997;60(5):281–90.
[54] Velraj R, Seeniraj RV, Hafner B, Schwarzer K. Heat transfer enhancement in a latent heat storage system. Solar Energy 1999;65:171–80.
[55] Seeniraj RV, Narasimhan NL. Performance enhancement of a solar dynamic LHTS module having both fins and multiple PCMs. Solar Energy 2008;82:535–42.
[56] Fukai J, Kanou M, Kodama Y, Miyatake O. Thermal conductivity enhancement of energy storage media using carbon fibers. Energy Conversion and Management 2000;41:1543–56.
[57] Fukai J, Kanou M, Kodama Y, Miyatake O. Effect of carbon-fiber brushes on conductive heat transfer in phase change materials. International Journal of Heat Mass Transfer 2002;45:4781–92.
[58] Fukai J, Kanou M, Kodama Y, Miyatake O. Improvement of thermal characteristics of latent heat thermal energy storage units using carbon-fiber brushes: experiments and modeling. International Journal of Heat and Mass Transfer 2003;46:4513–25.
[59] Xiao M, Feng B, Gong K. Thermal performance of a high conductive shape-stabilized thermal storage material. Solar Energy Material 2001;69:293–6.
[60] Vakilaltojjar SM, Saman W. Analysis and modeling of a phase change storage system for air conditioning applications. Applied Thermal Engineering 2001;21:249–63.
[61] Hed G, Bellander R. Mathematical modeling of air heat exchanger. Energy and Buildings 2006;38:82–9.
[62] Agyenim F, Eames P, Smyth M. Heat transfer enhancement in medium temperature thermal energy storage system using a multitube heat transfer array. Renewable Energy 2010;35:198–207.
[63] Bansal NK, Buddhi D. An analytical study of a latent heat storage system in a cylinder. Energy Conversion Management 1992;33:235–42.
[64] Papanicolaou E, Belessiontis V. Transient natural convection in a cylindrical enclosure at high Rayleigh numbers. Heat and Mass Transfer 2001;45:1425–44.

[65] Lacroix M. Numerical simulation of a shell and tube latent heat thermal energy storage unit. Solar Energy 1993;50:357–67.

[66] Raj VAA, Velraj R. Numerical simulation of free cooling system using phase change materials. In: Proceedings: international conference on energy and environment engineering ICEE 2009. Pondicherry, India: Pondicherry Engineering College; 2009.

[67] Pasupathy A, Velraj R, Seeniraj RV. Effect of double layered phase change materials in building roof for year round thermal management. Energy and Building 2008;40(3):193–203.

[68] Pasupathy A. Ph.D. Thesis. Building thermal management using phase change materials. Anna University; 2006.